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Dynamic Testing of Sign Truck Crash Barriers

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1/ INTRODUCTION

Road maintenance or construction work often requires the closing of traffic lanes by a protective device, so that a crew can work safely. Because of its mobility, a sign truck is often used. A sign truck protects the work crew in front of the truck, but it constitutes a severe hazard for an approaching out-of-control vehicle. The severity of this hazard can be greatly reduced or eliminated by complementing the truck with an impact attenuator, such as a crash cushion trailer or an attachment.

The crash trailers and attachments presently available on the market do not meet all the difficult safety and operational standards, and therefore they have failed to gain a wide acceptance. The Ministry, through its Policy Planning and Research Division, has evaluated various solutions developed in the United States. These solutions were satisfactory with regard to crash performance, but not with respect to mobility and durability while travelling longer distances during operation. The parts had a tendency to disintegrate. Furthermore, some of these designs could not handle impacting cars of different heights. Unfortunately, these shortcomings sometimes were discovered after the marketing of the prototype. The Ministry went into its own development program and avoided these pitfalls by first testing the operational features of the conceived prototypes. This partly explains why the project took such a long time to complete.

At present, crash barriers fall into two categories:

1/ Crushing material sitting on an additional axle and hitched to the truck, as in Figure 1a. This solution has a long crushing stroke (5 to 6 m). However, there are some limitations in maneuverability and stability of the truck-barrier system; and

2/ Crushing material supported by a frame which is attached to and cantilevers out from the rear of the truck, shown in Figure 1b. This solution combines a shorter crushing stroke (about 2 m) with optimum maneuverability and stability.

Maximum protection can only be achieved with a long crushing stroke; however, a trailer constitutes an additional piece of equipment and is more difficult to maneuver when backing up.

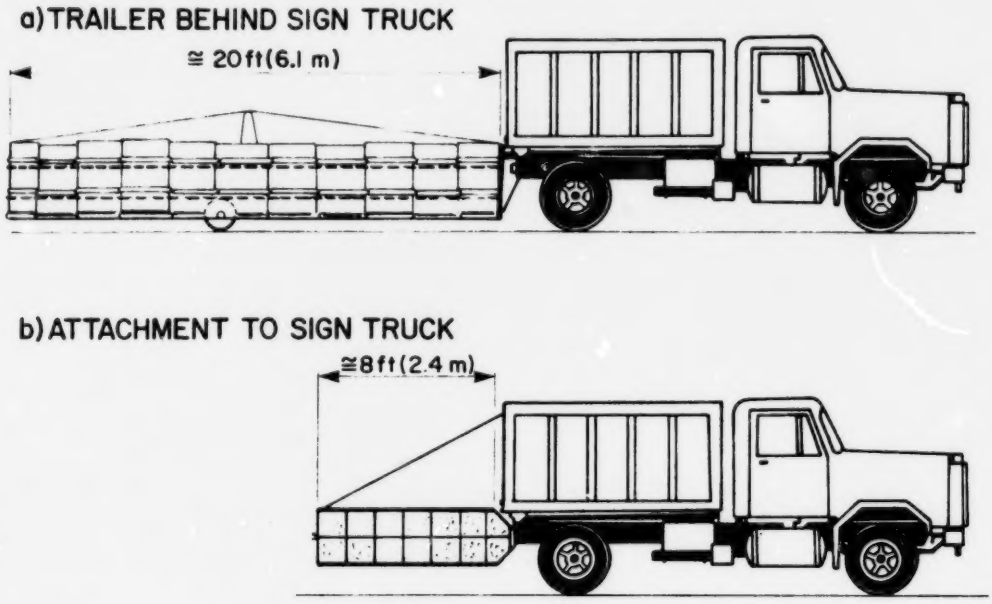


Figure 1/ Examples of Non-Stationary Crash Cushion Barriers Prototypes have been developed for both the trailer and the attachment solution.

2/ STANDARDS OF SAFETY AND TECHNICAL REQUIREMENTS

2.1/ General

In descending order of importance, the safety requirements are as follows.

1/ Safety of the crew working in front of the truck: for this, no attachment or trailer is needed. This is current MTC policy.

2/ Safety of innocent car occupants passing the location of a collision: the colliding vehicle must not rebound in front of other traffic. There should be no loose parts flying off at impact.

3/ Safety of occupants of the colliding car: this is the function of the crash cushion.

These safety concerns lead to the following design principles which must be observed when designing a crash cushion.

1/ Avoid loose parts that could become projectiles upon impact.
2/ Avoid stiff longitudinal members which could spear into the compartment of the colliding vehicle.
3/ Assure a safe, sufficiently low deceleration of the car's compartment.
4/ Maximize the energy absorbing capacity.
5/ Minimize the rebound.
6/ Minimize the crushing stroke length while maintaining sufficiently low deceleration.
7/ Assure integrity during operation. The design components must be resistant to frequent travelling shocks and vibrations.
8/ Assure crush stability for various car heights.

A critical factor for items 4 and 6 is the selection of crushing material. It was found that steel sheet metal, in the form of a "Texas" barrel design [1], best fulfills all the pertinent requirements.

2.2/ Occupant Safety Criteria

Previous R & D work on adequate standards for accelerations of passenger car compartments has been summarized in Reference [2]. Table 1 is a list of the tolerable acceleration or deceleration limits. These values are averages of the worst 50 ms within the time of crash impact.

Table 1/ Tolerable Acceleration Limits

Restraint Mode	Maximum Acceleration (G)		
	Lateral (Gy)	Longitudinal (Gx)	Vertical (Gz)
Unrestrained occupant	5	7	6
Lap belt	9	12	10
Lap belt and shoulder harness	15	20	17

The meaning of these limits is related to a probability of injury of 0.5, as illustrated in Figure 2.

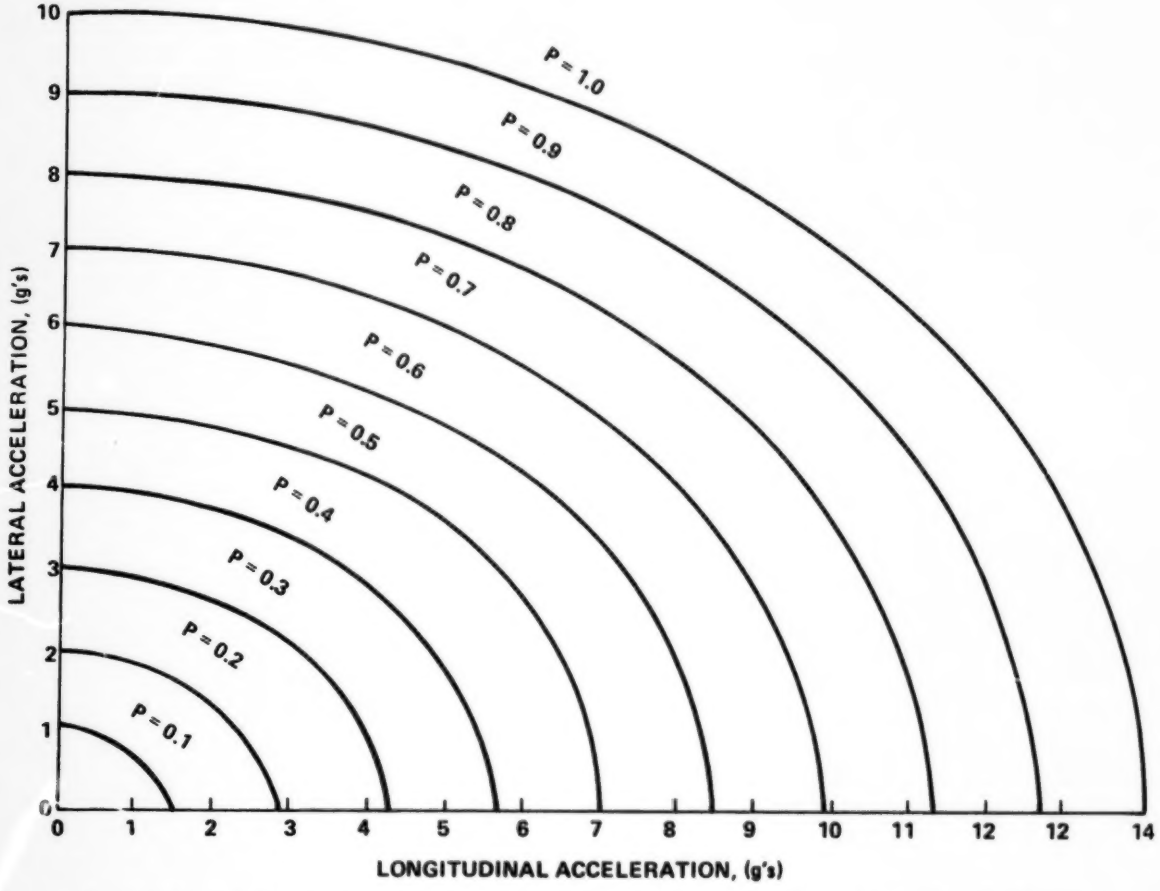


Figure 2/ Probabilities of Injury for an Unrestrained Occupant in a Car

The minimum crushing stroke length required to bring a car travelling at 100 km/h (27.78 m/s) to a full stop by a constant force of 7 g's (68.65 m/s^2) is:

$$S = \frac{(27.78)^2}{(2)\ (68.65)} = 5.6 \text{ m}$$

This is the crushing stroke length required to protect an unrestrained car occupant, which can be achieved by the comparatively long trailer barrier (Solution 1). For a fully restrained occupant, the maximum acceleration is 20 g's, and S = 2 m. This is a typical crushing stroke distance for an attached crash cushion, which provides a much lower level of protection (Solution 2). However, there is no such thing as a crushing material with a constant crushing force. Furthermore, a constant force is not even the most efficient design principle. This is explained in [3] and [4].

3/ CRASH CUSHION DESIGN FOR REAR IMPACT AND LONGITUDINAL DECELERATION

The shortest possible crushing stroke length for an impact attenuator can be achieved when its crushing force diagram closely follows the ideal force diagram represented in Figure 3. The upper limit of this diagram is the maximum permissible crushing force. The area under the curve represents the amount of energy dissipated through crushing of the material. The actual crushing force diagram must remain below the upper limit of the ideal force diagram. The area under the real curve must be greater than or equal to the area under the ideal curve. Thus, the actual crushing stroke length is always greater than X_k. Actual materials do not follow the ideal diagram. They generally have lower force values and higher maximum crushing distances.

The following steps are considered when plotting an ideal crushing force diagram such as Figure 3 (see also [3]).

1/ Select the impact velocity, usually the road's speed limit: V (m/s).

2/ Select a minimum car weight: m_1 (kg) and a maximum car weight: m_k (kg), thus specifying the range of car weights to be protected.

3/ Select the maximum permissible deceleration; a_m (m/s^2) from Table 1.

4/ Calculate F_1, the limiting crushing force required to protect the smallest car.

$$F_1 = m_1 a_m$$

5/ Calculate S_1, the corresponding crushing stroke of the crash cushion.

$$S_1 = \frac{M}{m_1 + M} \cdot \frac{V^2}{2 a_m}$$

Where M is the combined mass of the sign truck and the impact attenuator.

6/ Select several values for m_i, between m_1 and m_k. For each m_i, calculate the corresponding values of the crushing force (F_i) and the crushing stroke (X_i).

$$F_i = m_i \cdot a_m$$

$$X_i = \frac{V^2}{2a_m}\left[\ln\left(\frac{m_i}{m_1}\right) - \ln\left(\frac{M + m_i}{M + m_1}\right) + \frac{M}{M + m_i}\right]$$

This establishes the ascending part of the diagram.

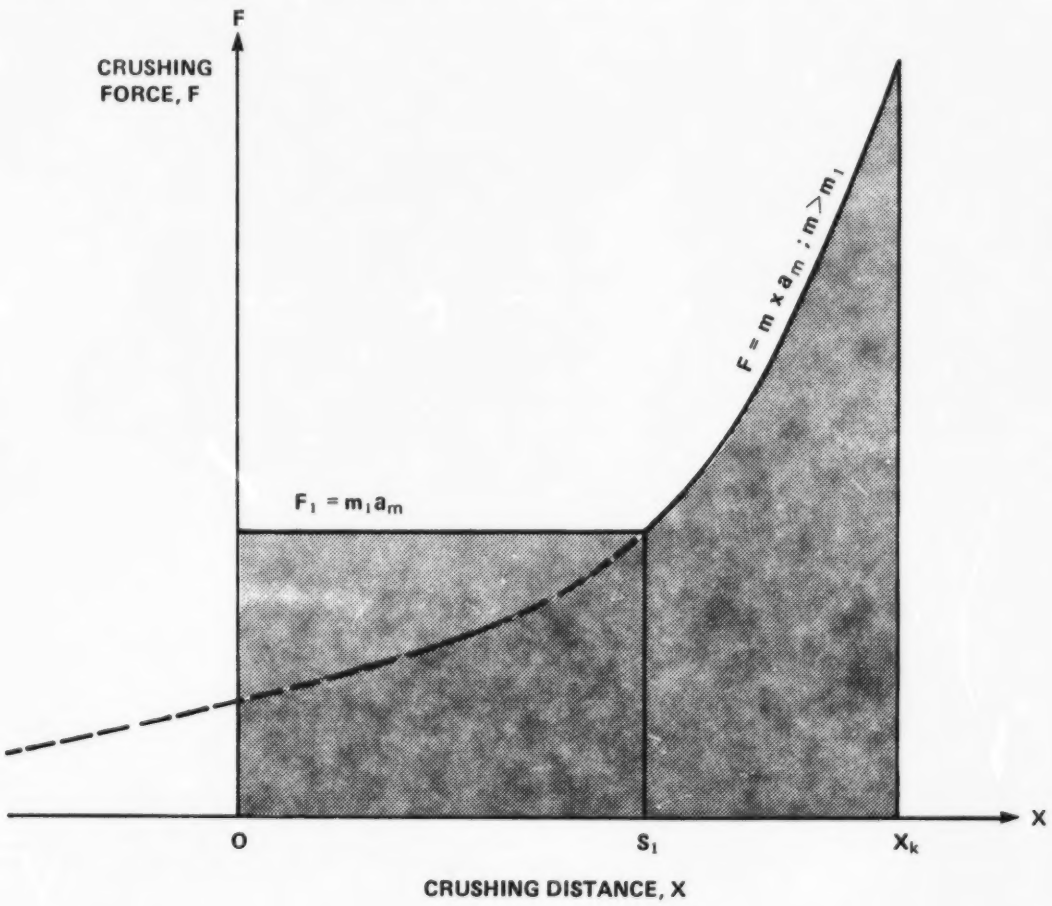


Figure 3/ Crushing Force Diagram for Maximum Tolerable Deceleration, a_m

4/ ALTERNATIVE SOLUTIONS

In order to satisfy the aforementioned requirements, the R & D Division of MTC has designed and developed two crash attenuators, corresponding to the two solutions that have already been discussed. These are:

(1) Crash Barrel Trailer ("Texas" design, with bolted connections)
(2) Crash Barrel Attachment

4.1/ Barrel Trailer

This is a modification of the Texas barrel trailer [1] and, as represented in Figures 1a and 4, is composed of #18 (1.2 mm) paint drums, 0.9 m high and 0.6 m in diameter, with 405 mm holes in the tops and bottoms. The drums are attached to each other with bolts, positioned as near as possible to the tops and bottoms of the drums. A suspension system of adjustable steel cables adds stability. The barrel assembly is supported by a two-wheel axle located in the middle of the trailer.

4.2/ Barrel Attachment

As shown in Figure 5, the barrel attachment consists of twenty barrels identical to those used for the crush trailer, and joined with bolts in the same manner. The attachment can be fitted to the back of any service vehicle.

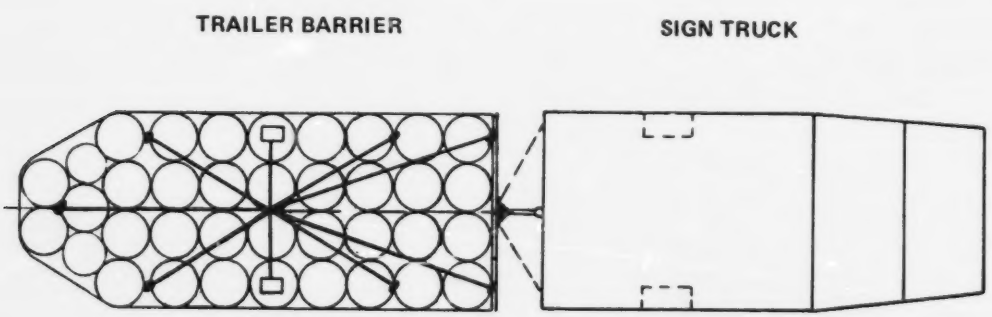


Figure 4/ Top View of Barrel Trailer Assembly

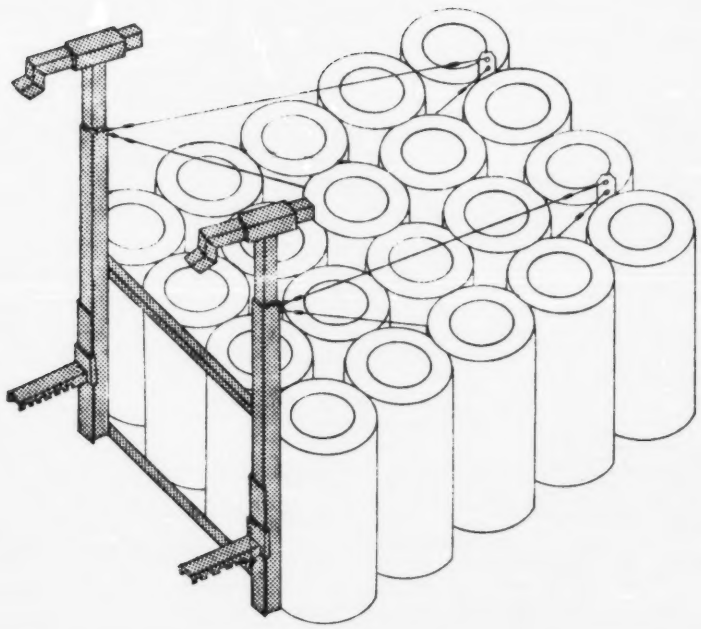


Figure 5/ Barrel Attachment

5/ COMPARISON OF MAJOR CHARACTERISTICS OF THE ALTERNATIVE SOLUTIONS

When selecting a crash attenuator for a specific purpose the following characteristics should be considered:

1/ Crash performance
2/ Operational Comfort
3/ Cost

5.1/ Performance

The performance is basically a matter of the quality of the crushing material and the length of the attenuator. Both solutions use steel as the basic material. This gives good integrity, little rebounding effect, and sufficient plastic deformation upon impact, when properly designed. The principle is to maximize energy absorption by crumpling the barrels while minimizing the total weight of material used. The trailer is superior in impact protection because of the longer stroke length.

5.2/ Operational Comfort

The trailer can be pulled by any service truck. It has a simple joint similar to that of a camper trailer. The hitch is supplemented by two side chains attached to the bumper of the truck. The chains help stabilize the trailer during a collision by limiting the turning angle when under tension. Due to the length, and other structural features of the trailer, driving should be limited to 80 km/h.

The attachment is held in place with a specially designed hanger on the top, and a chain grip device on the bottom. The driving speed is not affected, and expertise in driving with a trailer is not required. A dump truck should be used.

5.3/ Cost

Cost figures for both solutions should be established by estimates based on the manufacturing of at least a dozen prototypes each. The trailer would probably cost more because of the additional costs of wheels and the larger number of barrels. On this basis a quotation was obtained in 1980 (August), in the amount of $2600.

6/ TESTING OF COMPONENTS AND CONNECTIONS

Paint drums have been tested for their static crushing force, as reported in [5] and [6]. Figure 6 is a typical crushing force diagram for a paint drum. The test results are summarized in Figure 7, and can be used to obtain appropriate design data.

The critical factor for both solutions was the method of joining the drums to each other. The first prototype had welded connections, which tended to break after 1000 to 2000 km of regular driving. As such, welded and bolted connections were compared in laboratory tests conducted at the University of Toronto. The tests were conducted in accordance with Figure 8, at a rate of 200 cycles/minute.

The welded connections failed after 3000 to 7000 load cycles, but the bolted connections had a much greater fatigue resistance and did not fail even though more than 120 000 load cycles were applied. Therefore, bolted connections were used in the proposed prototype. In order to avoid cutting of the barrel sheet metal by vibrational forces, the bolted connection should be designed with hard rubber washers and spacers.

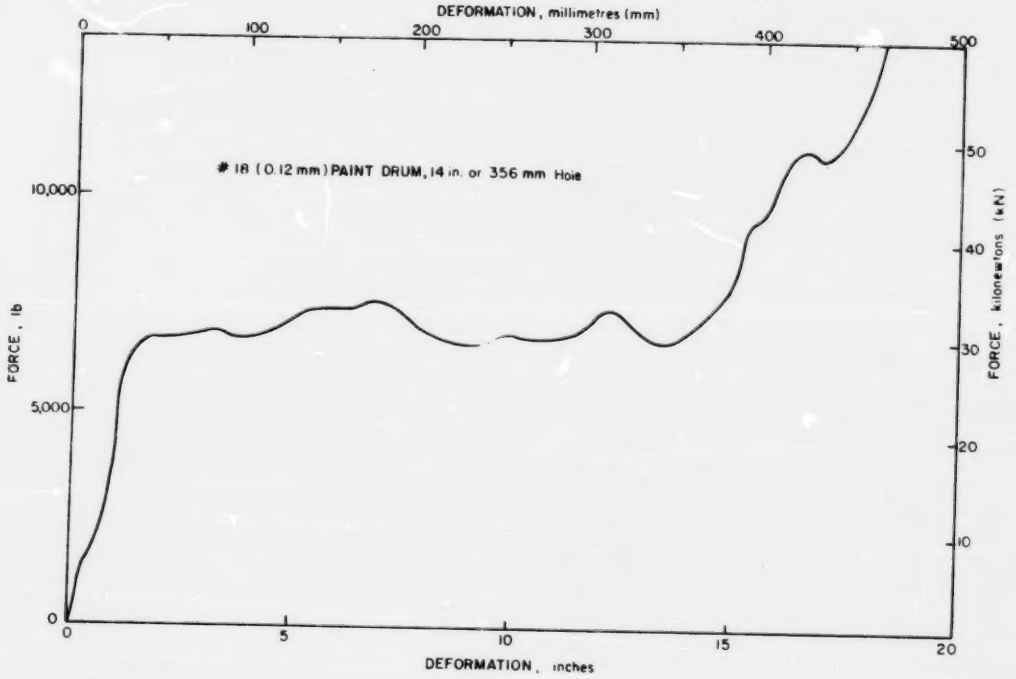


Figure 6/ Crushing Force Diagram on #18 Gauge Steel Paint Drum

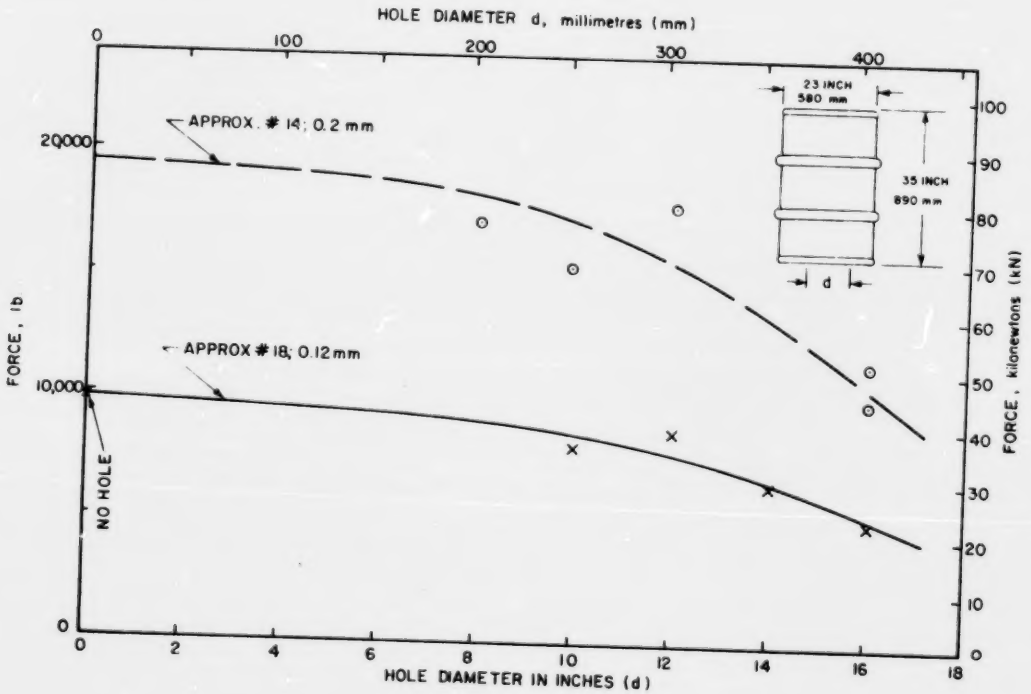


Figure 7/ Results of Drum Component Testing

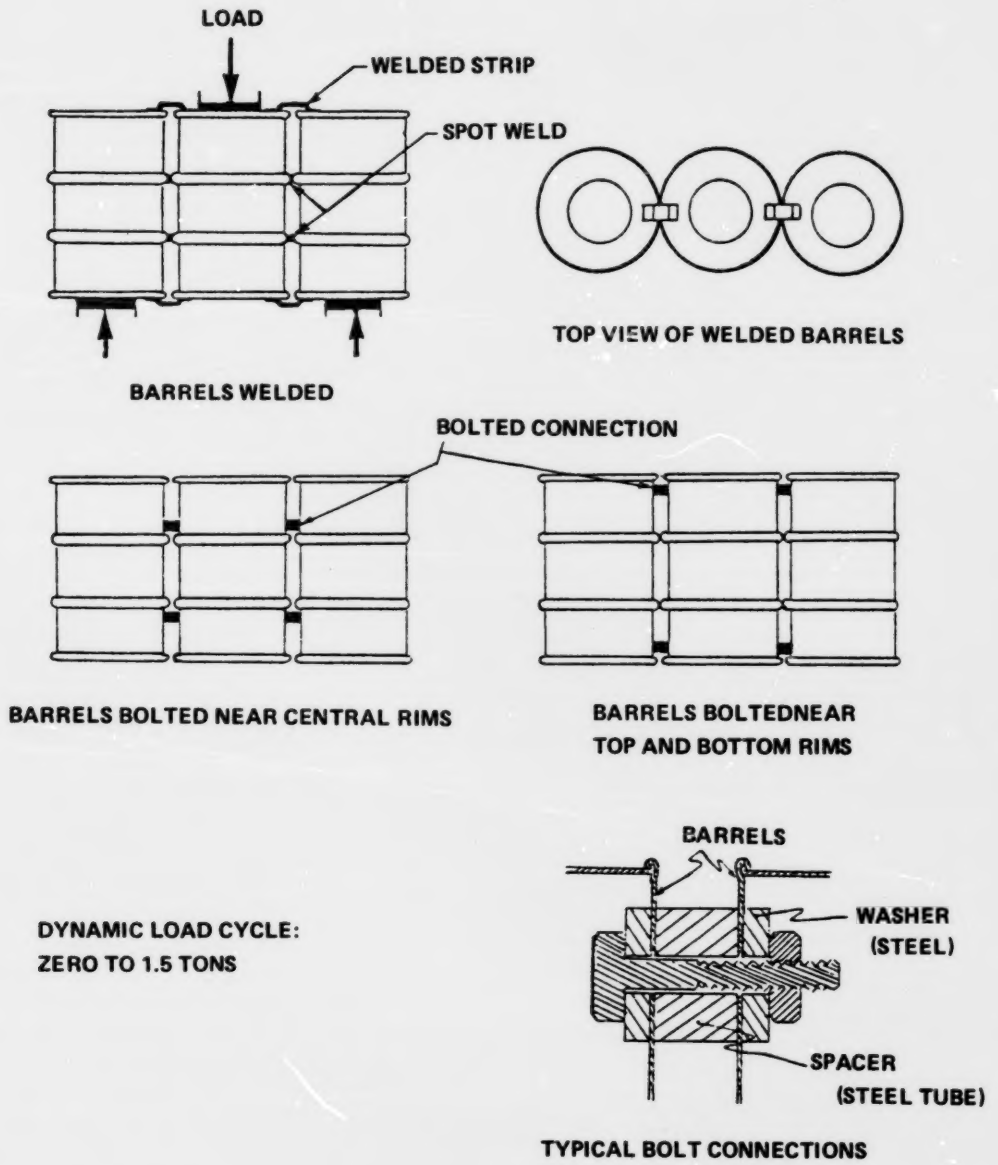


Figure 8/ Endurance Test of Barrel Connections

7/ ACCIDENT EXPERIENCE WITH THE PROTOTYPE

As already discussed, the energy absorbing capacity of the barrel trailer and its protectiveness when hit by an out-of-control vehicle are expected to be greater than those of a barrel attachment. Furthermore, the trailer can be designed to provide lower decelerations for given impact velocities. All of these qualities are direct results of the trailer's greater crushing stroke length.

During a three month test-period on Ontario highways, the crash trailer was involved in two accidents. The accident reports are summarized below.

First Collision

The collision occurred on June 22, 1975 at 5:25 a.m. on the eastbound Queen Elizabeth Way, east of Dixie Road. The sign truck driver reported the accident as follows: "The sign truck pulling the barrier trailer was travelling at 10 to 13 km/h in the center lane behind a striper in operation, when the trailer barrier was hit in a glancing blow fashion by a compact car with an estimated speed of 105 to 113 km/h. Only one barrel was damaged (see Figure 9). The car was redirected. It crossed two lanes and drove away without stopping." Without the trailer barrier, the car would certainly have hit the back of the sign truck. Severe damage and injuries could have been the result.

Second Collision

The accident occurred on July 14, 1975, on Highway 400 northbound. It was reported as follows:
The sign truck equipped with a barrel trailer was travelling with a speed of 16 km/h behind a striper in operation. The trailer was hit eccentrically on a slight angle by an empty 3-ton truck, travelling at about 100 km/h. All barrels on the colliding side of the trailer were crushed (see Figure 10), and the trailer was pushed underneath the sign truck. The driver of the impacting vehicle did not suffer any injury, although the

damage to the barrel trailer was beyond repair. If the barrel trailer had not been present, the driver would probably have suffered serious injuries by hitting the rear of the sign truck.

As a result of these incidents, the trailer design was modified in accordance with a close evaluation of the accident performance.

Third Collision

Another trailer of the same (modified) design was smashed in an accident on October 30, 1980, on N/B QEW, North End of Burlington Sky Way Bridge. A stationwagon hit the back of the trailer at about 70 km/h. The car was damaged but the seat-belted driver was unharmed. The truck suffered no damage, but the trailer was a total loss (Figures 11, 12, 13, 14).

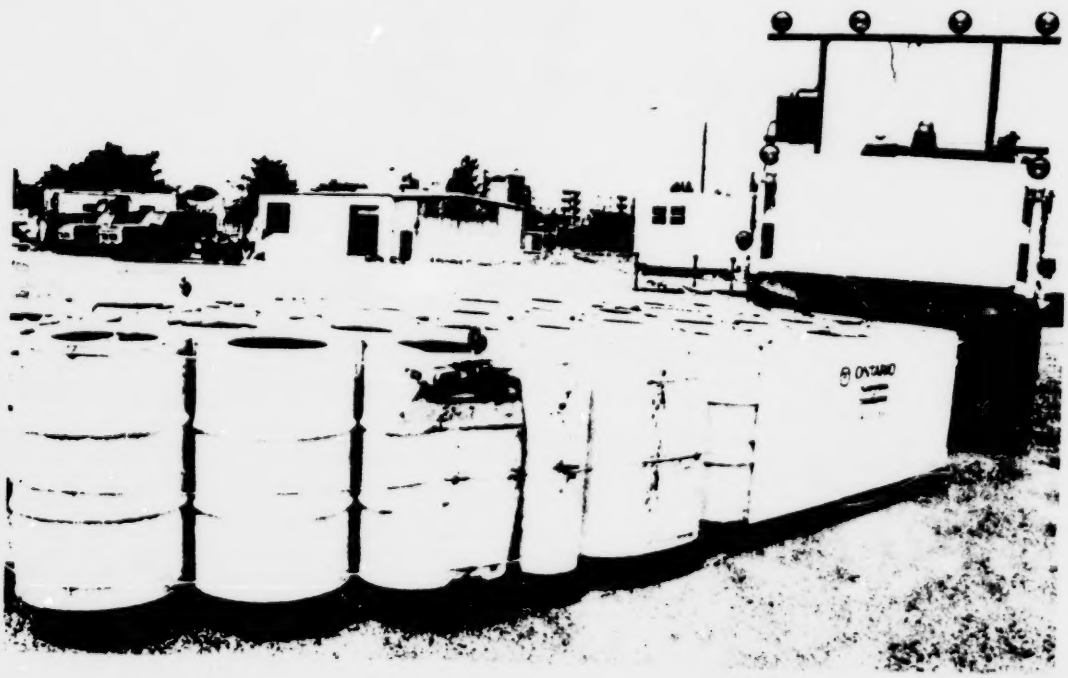


Figure 9/ Damaged Crash Trailer after Glancing Blow Collision with Car.

Figure 10/ Crash Trailer Wreck After Angular Rear Collision of Pickup Truck

Figure 11/ Automobile After Collision with Barrel Trailer

Figure 12/ Side View of Barrel Trailer after Collision

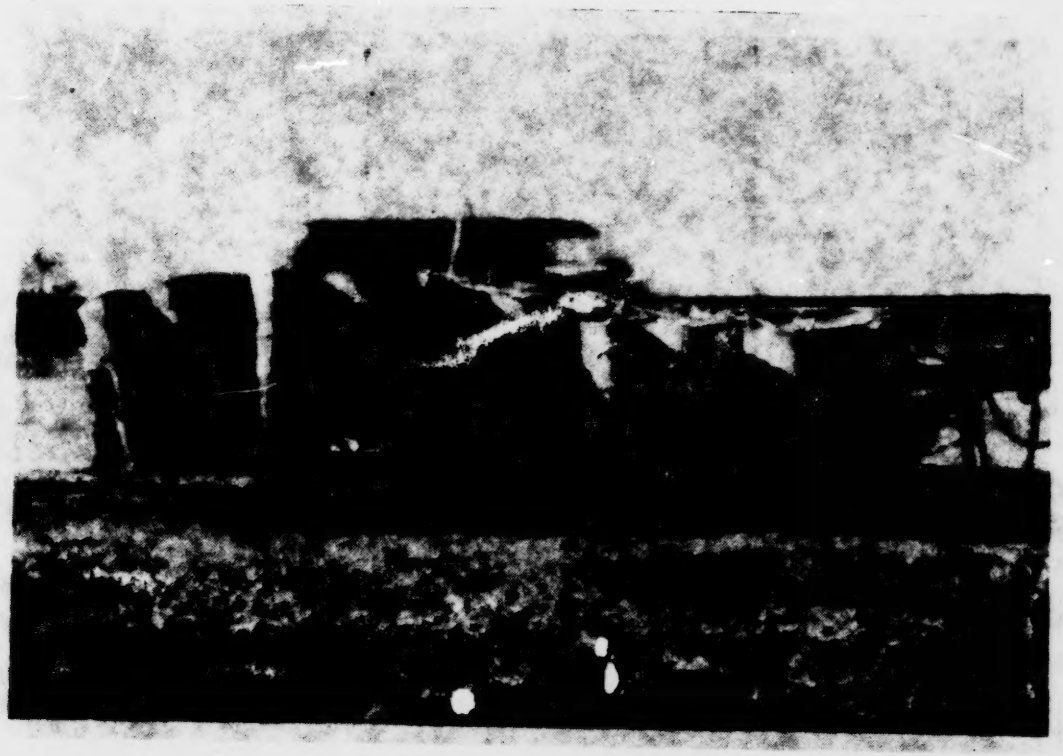
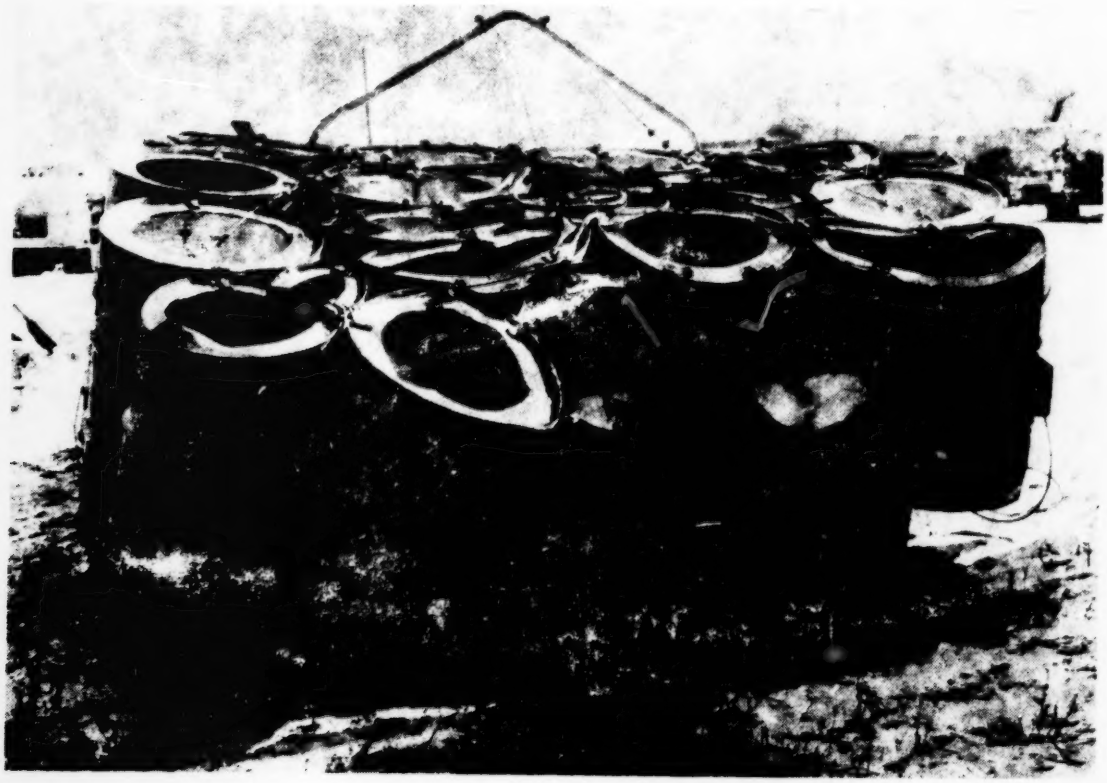


Figure 13/ Barrel Attachment and Truck after Collision

Figure 14/ Closeup View of Barrel Trailer after Collision



8/ DYNAMIC TESTING OF PROTOTYPES

8.1/ Testing of Barrel Trailer

The barrel trailer was tested by Calspan Corporation in Buffalo, N.Y. in August, 1978. As shown in Figure 15, the trailer was hitched to a 5845 kg truck, with the parking brake on and the transmission in neutral. A full-size (1980 kg) car collided with the rear of the trailer, with an impact speed of 97.5 km/h, simulating a collision along the central axis. Figure 12 shows the post-impact condition of the barrel assembly and the impacting vehicle. Details of the test and analysis are in Appendix A.

Figure 15/ Trailer and Impacting Car

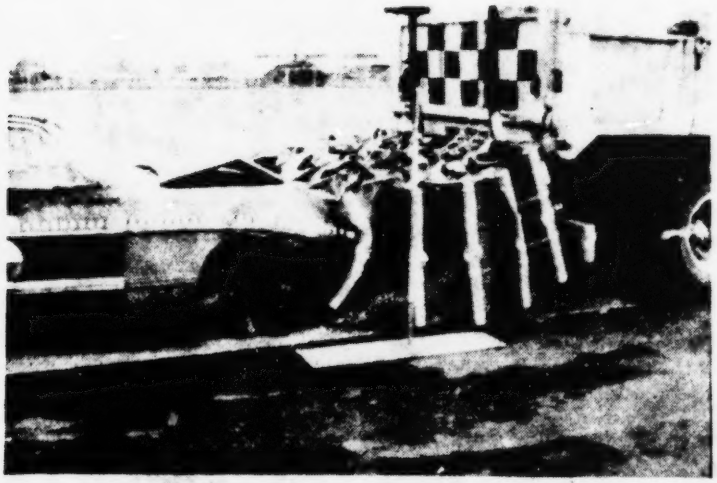


Figure 16/ Barrier Configuration After Impact.

The main purpose of the test was to compare the forward deceleration of the car and/or its passenger compartment with the proven standards, and also with the design prediction model. From Figure 13 ([5], [6]), an average deceleration of 7.3 g's is required for the test car of 1980 kg. This is independent of the impact velocity and the truck mass, as long as there is sufficient energy absorption through crushing barrels.

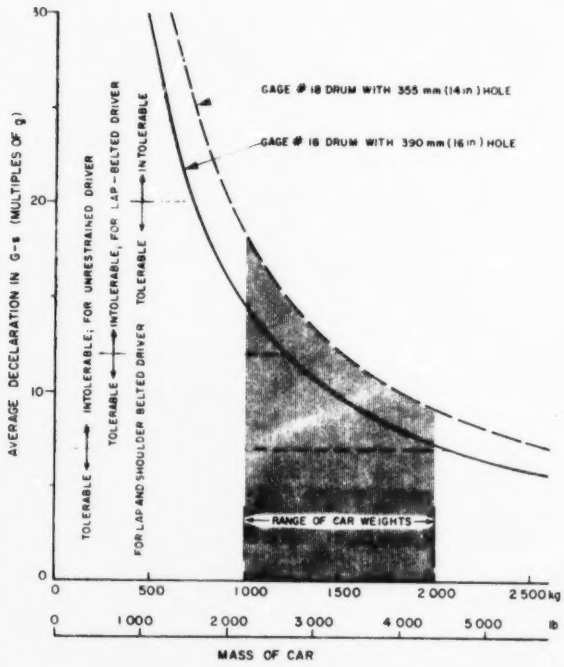

AVERAGE DECELARATION IN G-s (MULTIPLES OF g)
30
20
10
0
GAGE # 18 DRUM WITH 355 mm (14 in) HOLE
GAGE # 18 DRUM WITH 390 mm (16 in) HOLE
TOLERABLE — INTOLERABLE; FOR UNRESTRAINED DRIVER
TOLERABLE — INTOLERABLE, FOR LAP-BELTED DRIVER
FOR LAP AND SHOULDER BELTED DRIVER TOLERABLE — INTOLERABLE
RANGE OF CAR WEIGHTS
0 500 1000 1500 2000 2500 kg
0 1000 2000 3000 4000 5000 lb
MASS OF CAR

Figure 17/ Average Car Deceleration

The test results reveal a somewhat lower average crushing force of 6.1 g's. However, as seen in Figure 18, the worst 50 ms average is somewhat larger: about 8.5 g's. These values are inversely proportional to the car weight, as shown in Table 2, below. From this table of expected values, it is seen that occupants of cars weighing less than 1500 kg require a shoulder harness if they are to be fully protected.

Table 2/ Car Mass and Deceleration

Restraint Required	Mass of Car (kg)	Average Deceleration (g's)
Lap Belt and Shoulder Harness	850	20
	1000	17
	1250	14
Lap Belt Only	1500	11.5
	1750	10
	2000	8.5

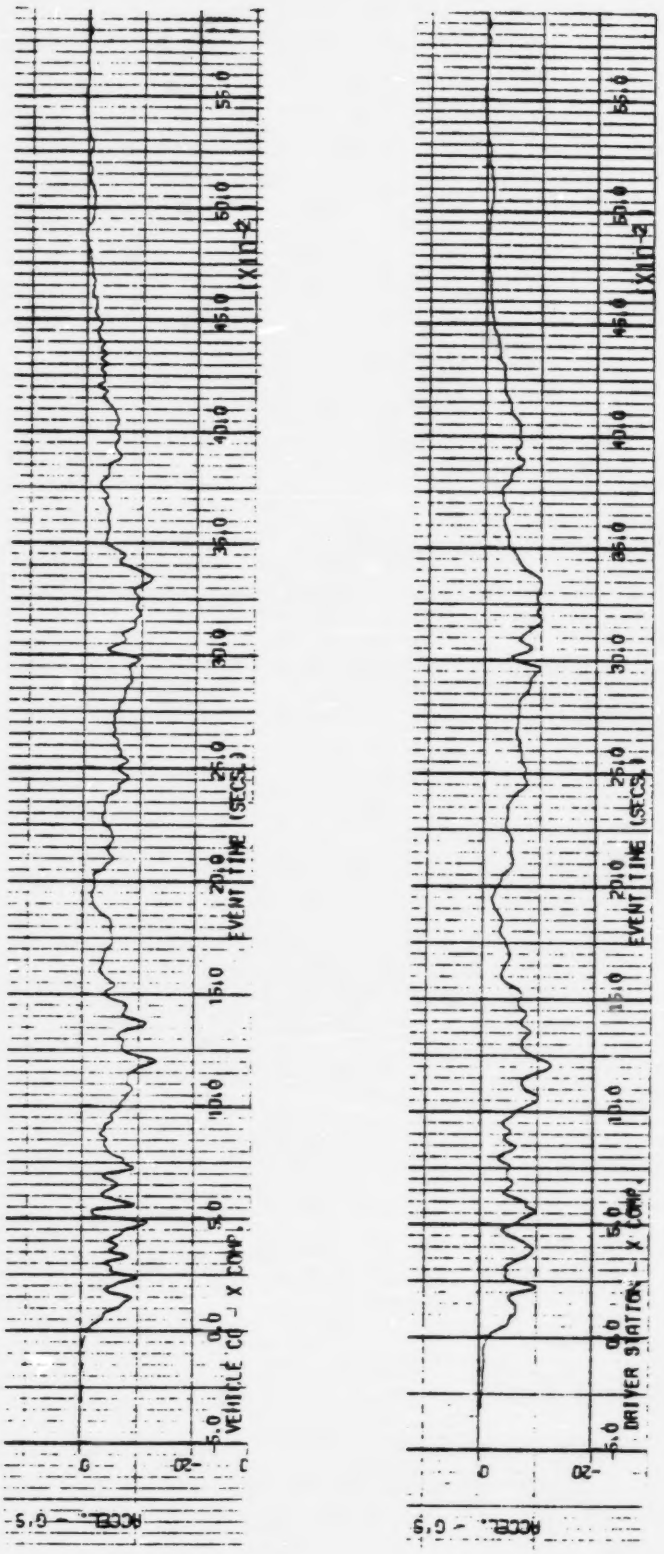


Figure 18/ Accelerometer Readings for Barrel Trailer Test

Furthermore, the barrel trailer provides insufficient protection for occupants of vehicles weighing less than 850 kg, because the barrels are too rigid.

The prototype trailer exhibited sufficient stability. It absorbed energy through the smooth and uniform crushing of the barrels. The supporting truck suffered only minor damage. Thus, the barrel assembly with bolted connections, properly suspended on the middle frame over the wheels, can be recommended as adequate standard equipment.

8.2/ Testing of Barrel Attachment

The barrel attachment was tested by Calspan Corporation in July, 1979. The truck with barrel attachment, shown in Figure 19, had a combined weight of 8340 kg. The truck transmission was in neutral, and the parking brake was on. The 1880 kg (full-size) car, travelling at 60 km/h, collided with the barrel attachment along the central axis.

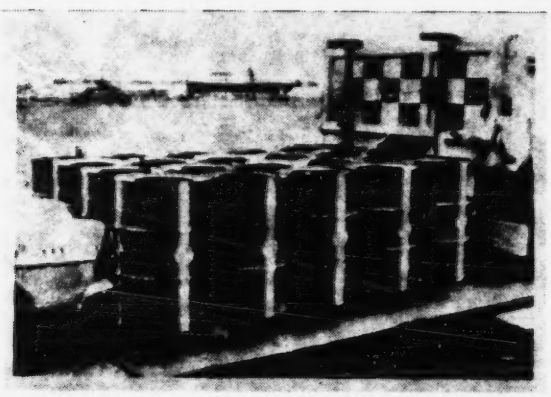


Figure 19/ Barrel Attachment on Truck

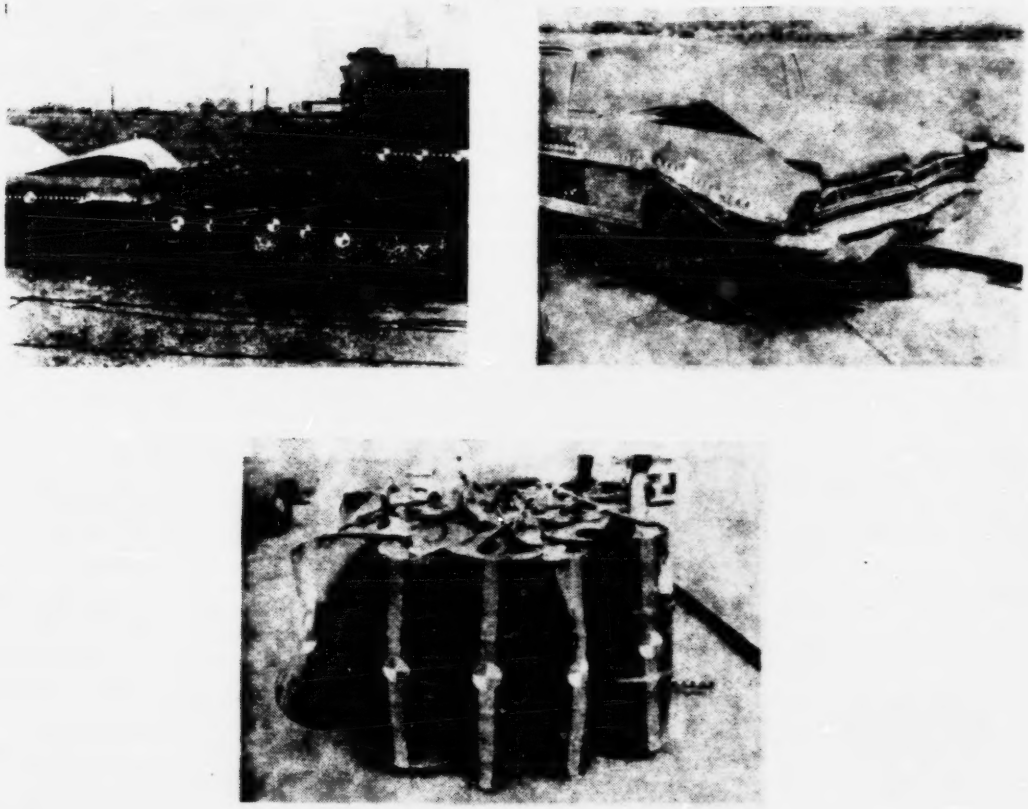
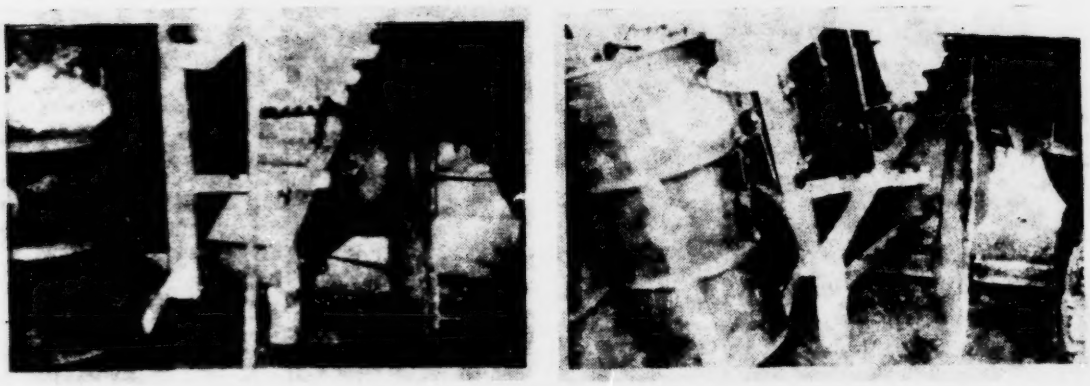


Figure 20/ Barrier Deformation Pattern

Figure 20 shows the post-impact condition of the car and the barrels. The attachment was crushed in a uniform and controlled manner. The impacting vehicle had negligible pitch, yaw, and roll. There was no debris scattered about the site.

The transference of the impact forces to the truck caused minor damage to the barrier attachment hardware and the truck bumper assembly, as shown in Figure 21. One of the attachment chains broke, and the barrel attachment slid forward several inches beneath the truck.

Details of the test and analysis are in Appendix B.



a) BEFORE IMPACT

b) AFTER IMPACT

Figure 21/ Bumper Connections

The barrel attachment was also compared to the design prediction model of Figure 21. The model indicates an average deceleration of 7.6 g's. The average deceleration from the test is 5.9 g's, based on the measured impact speed and stopping distance. Thus, the model has again over-estimated the deceleration. However, as shown in Figures 22 and 23, the highest deceleration average over 50 ms is 7.5 g's, which is closer to the value suggested by the model.

The barrel attachment has been shown to be comparable to the trailer, though not for high speeds. To escape injury, an approaching driver would have to slow down to approximately 60 km/h, or be wearing a seat belt with shoulder harness. The attachment would be ideal for areas where the speed limit is lower, and has the added benefit of being more maneuverable.

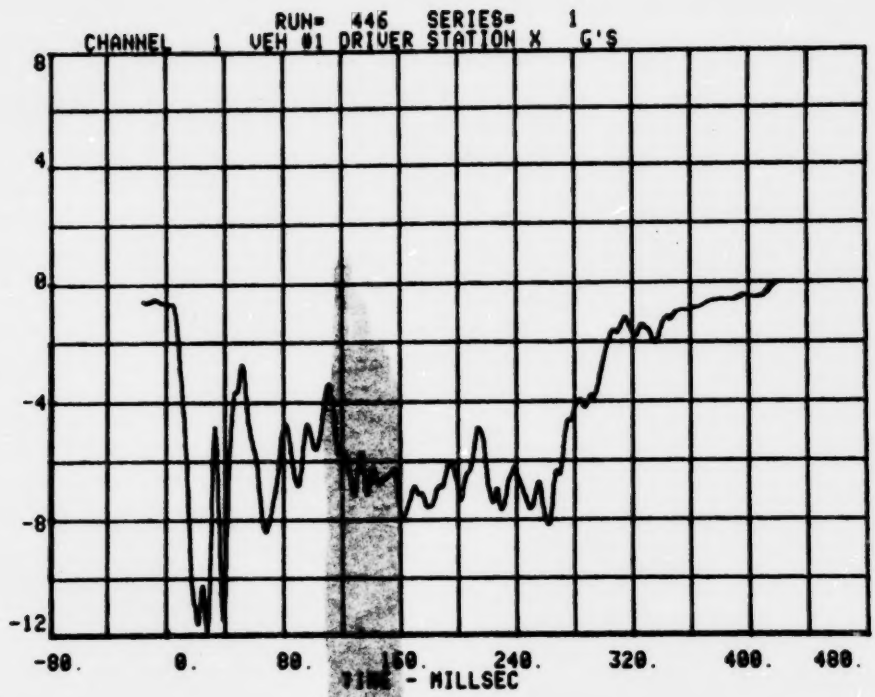


Figure 22/ Driver Station Accelerometer Readings

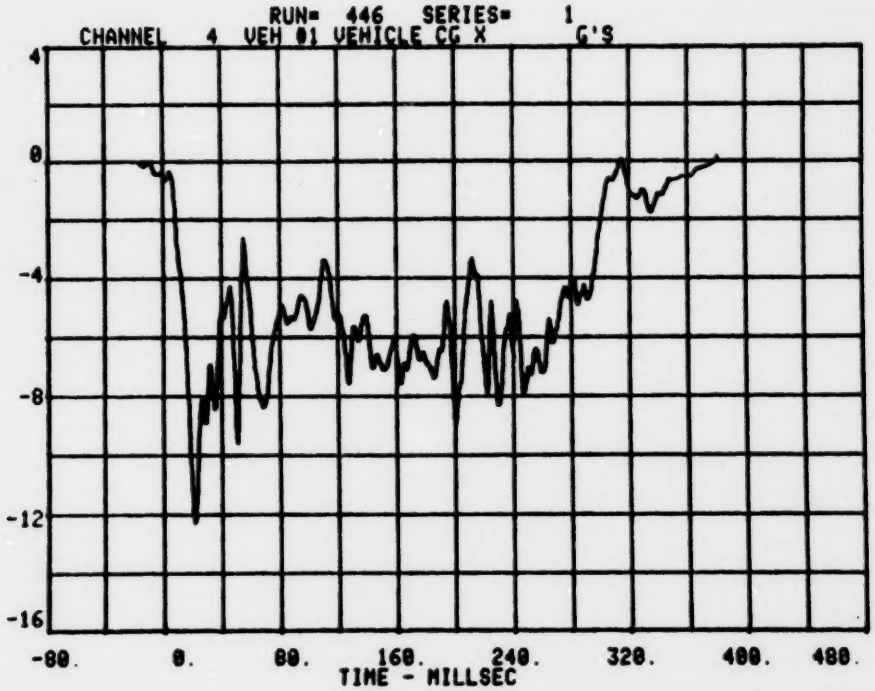


Figure 23/ Vehicle Centre of Gravity Accelerometer Readings

9/ CONCLUSIONS AND RECOMMENDATIONS

1/ During the course of this development work, several other types of crash cushions were tested: resilient sheets of plastic with cellular micro-structure, and a trapezoidal steel box with two diaphragm walls made from car body gauge steel. Testing at Calspan Corporation revealed basic weaknesses in both designs.

(a) A sensitivity to the height and centre of gravity of the impacting car: the test cars tended to underride or ramp over the crash cushion.
(b) A lack of strength and stability.
(c) A difficulty in controlling the dynamic crushing force.

2/ The Texas Barrel crash cushion with bolted connections did not have any of these weaknesses. Therefore, it is highly recommended.

3/ Because of its higher degree of protection, the barrel trailer is recommended for use on high-speed roads (100 km/h) with high traffic density. On slower, less used roads, the barrel attachment is recommended because it offers sufficient protection, and is more maneuverable and less expensive than the trailer.

Appendix A

DYNAMIC TESTING OF CRASH BARREL TRAILER

Table A1 is a list of the basic dimensions of the service truck and the impacting vehicle for this test.

Table A1/ Test Vehicle Weights

Striking Vehicle:		Pontiac Grandville 1971	
LF	567	LR	426
RF	572	RR	417
Front	1139 kg	Rear	843 kg
	Total: 1982 kg		
Wheel Base			319.0 cm
C.G. Aft of Front			135.6 cm
Service Truck			
LF	1542	LR	1537
RF	1411	RR	1356
Front	2953 kg	Rear	2893 kg
	Total: 5846 kg		
Wheel Base			371.5 cm
C.G. Aft of Front			183.9 cm

The following observations were measured at the completion of the test:

- the barrel system was crushed a total of 389.4 cm;

- the trailer wheels moved ahead 8.50 m.

Striking vehicle damage was limited to the frontal section, as shown in Figure 12. The vehicle displacement during the 0.49 second acceleration event was 6.1 m, for an average longitudinal acceleration of 6 g's. The vehicle came to rest 10.45 m from the point of impact. No significant pitch, yaw, or roll was noted in the data film.

The sign truck cab was accelerated to a maximum velocity of 21.7 km/h, 0.48 after impact, at which time the truck had moved 127 cm. The truck moved forward a total of 5.70 m before coming to rest. Only minor repairs were required to refurbish the truck to its original condition.

Appendix B

DYNAMIC TESTING OF CRASH BARREL ATTACHMENT

The impacting vehicle was a 1880 kg Ford Wagon, with the centre of gravity located 153.4 cm behind the front axle. The sign truck, including the crash attachment, weighed 8342 kg. The test results are as follows:

- the barrel system was crushed 177.8 cm.

Damage to the striking vehicle was limited to the frontal section, as shown in Figure 16. Based on an impact velocity of 60.0 km/h and a stopping distance of 2.39 m, the average deceleration was 5.9 g's. There was no significant pitch, yaw, or roll.

The truck cab reached a maximum speed of 11.3 km/h. The truck moved 1.47 m before coming to rest (see Figure B1).

Only minor truck bumper repairs were required to refurbish the truck to its original condition.

Appendix B

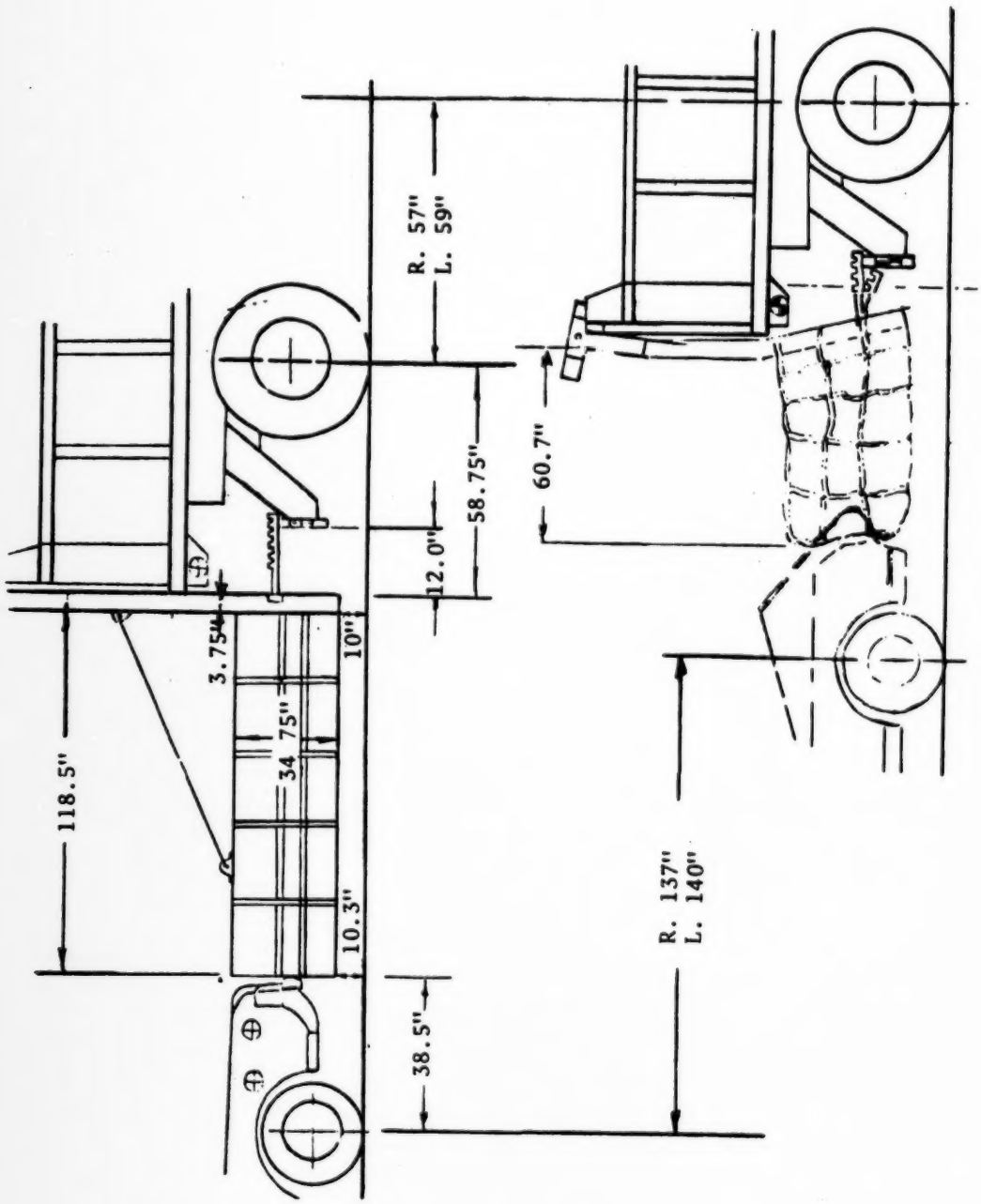


Figure B1/ Pre- and Post-Impact Scene Sketch

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